# NASA Contractor Report 165665

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# Main Rotor Six Degree-of-Freedom Isolation System Analysis

L. Eastman

CONTRACT NAS1-16168
MAY 1981



National Aeronautics and
Space Administration

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Attention: Mr. James Y. Taylor, Contracting Officer, Mail Stop 126

Contract No. NAS1-16168, Main Rotor Six Degree-Of-Freedom Isolation System Analysis, Submittal of Final Report (Potential Missing Pages)

Reference: (a) Sikorsky Engineering Letter (SEL) 5839 dated 15 June 81
(b) NASA Letter NAS1-16168(126/MSH) dated 13 Feb. 81

Enclosure: (1) NASA Contractor Report 165665 (pages 7 & 8)
(2) Distribution List

The final report entitled "Main Rotor Six Degree-Of-Freedom Isolation System Analysis" was inadvertently submitted with pages 7 and 8 missing. These pages are herewith submitted.

Respectfully,

UNITED TECHNOLOGIES CORPORATION

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LBE:mwm

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| | |
|---|---|
| A/C | Aircraft |
| CG | Center of Gravity |
| DGW | Design Gross Weight, kg (lb) |
| DOF | Degree-of-Freedom |
| $F_x$ | Longitudinal main rotor force, N (lb) |
| $F_y$ | Lateral main rotor force, N (lb) |
| $F_z$ | Vertical main rotor force, N (lb) |
| g | Acceleration of gravity, $m/sec^2$ ($in/sec^2$) |
| GENHEL | General Helicopter computer simulator model |
| GW | Gross weight, kg (lb) |
| K | Isolator bar stiffness, N/cm (lb/in) |
| $M_D$ | Isolator dynamic mass, kg ($lb\text{-}sec^2/in$) |
| MGB | Main Gear Box (transmission) |
| $M_x$ | Main rotor roll moment, N-m (lb-in) |
| $M_y$ | Main rotor pitch moment, N-m (lb-in) |
| $M_z$ | Main rotor yaw moment, N-m (lb-in) |
| NP | Blade passage frequency (N/REV), HZ |
| $N_R$ | Normal rotor speed, HZ |
| $N_z$ | Load Factor |
| R | Distance from the isolator upper body attachment (pivot) point to the center of gravity of the dynamic mass, cm (in) |
| r | Distance between the isolator upper and lower body attachment (pivot) points, cm(in) |
| R&M | Reliability and Maintainability |
| $V\text{-}N_z$ | Load factor vs airspeed diagram (flight envelope) |
| $\omega_a$ | Isolation system antiresonant frequency, rad/sec |
| $\omega_r$ | Isolation system resonant frequency, rad/sec |

## 1.0 INTRODUCTION

The development of vibration control concepts has been ongoing for many years. This research has produced an extensive list of approaches which can be used to meet the ever increasingly stringent requirements for ride comfort. The list covers a wide range of options including rotorhead absorbers and blade mounted pendulum absorbers, transmission isolation, fixed system absorbers, and airframe and rotor tuning by structural design. Table 1 summarizes the variety of approaches which have been evaluated, some of which are in use on present Sikorsky helicopters. In addition to these approaches, extensive work is presently being focused on Higher Harmonic Control as a method of controlling high frequency rotor airloads and thus vibration. In the past, the vibration control package has been more or less tailored for each individual aircraft design with the package crystalizing during the flight development program in order to satisfy the critical aircraft needs. As the requirements for vibratory levels at personnel locations have become lower and lower (now approaching the threshold of perceptibility), the weight of this vibration control package as a percentage of gross weight has increased. In the interest of mission performance, fuel conservation, as well as reliability and maintainability, the necessity to lower the vibratory environment of the aircraft at a lower weight penalty is quite clear. Pursuant to that goal, the concept of transmission isolation becomes inviting in that not only can the vibratory environment of the crew be reduced, but the overall force levels which excite into the airframe from the rotor are reduced, thus lowering the overall airframe response and improving reliability and maintainability (R&M).

A transmission isolation system was first designed at Sikorsky in the early 1970's when a soft-active system for the CH-53A (Reference 1) was designed, fabricated, and shake tested. The next pass at isolation was taken during the design phase of the S-69 (ABC), where a system was planned to soft mount the transmission in the roll degree-of-freedom. The configuration was a focused passive soft system which placed the natural frequency well below NP to provide the necessary transmissibilities. Transmission isolation again appeared during the detail design of the S-72 (RSRA). Unlike the ABC, this concept employed a focused soft active system which provided isolation in 4 degrees-of-freedom (roll, lateral, pitch and longitudinal) while providing interface load measuring capabilities (Reference 2 and 3). As with the ABC, the system was soft to place the modal frequencies well below NP. The active feature reduces the critical interface deflections.

VIBRATION CONTROL APPROACHES

| Model | Design GW (kg) | Design GW (lb) | $V_{MAX}$ (KN) | Main Rotor Type | No of Blades | Rotor Bifilar Absorber | Blade Pendulum Absorber | Fuselage Absorber | Structural Design | Rotor Design | Transmission Isolation | Hor Stab Isolation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SH-60B | 8,845 | 19,500 | 182 | Art | 4 | *3P Inplane | | *Nose<br>*Cabin | ✓ | | | * ✓ |
| UH-60A | 7,484 | 16,500 | 194 | Art | 4 | *3P Inplane<br>5P Inplane<br>4P Vert | 3P Vert<br>4P Vert | *Nose (Conv & Self-Tune)<br>*Cabin<br>Cockpit | ✓ | | | * ✓ |
| S-76 | 4,536 | 10,000 | 170 | Art | 4 | *3P Inplane<br>4P Inplane<br>*5P Inplane | 4P Vert | *Nose<br>Cockpit | ✓ | | Roll & Pitch | |
| CH-53E | 25,400 | 56,000 | 195 | Art | 7 | | | | ✓ | | | |
| ABC | 5,670 | 12,500 | 250 | Rigid Co-axial | 3/3 | | | Cabin (Self-tuned) | ✓ | | Roll Only | |
| RSRA(Helo)<br>(Comp) | 8,346<br>11,783 | 18,400<br>26,000 | 160<br>300 | Art | 5 | 4P Inplane | | Nose | | | Roll & Pitch (Active) | |
| CH-53 | 15,876 | 35,000 | 195 | Art | 6 | | | | ✓ | | 3-DOF (Active) | |
| S-64 | 17,236 | 38,000 | 115 | Art | 6 | | 6P Vert | | ✓ | | | |
| S-61 | 7,711 | 17,000 | 165 | Art | 5/6 | *4P Inplane | | *Nose | ✓ | | | |
| S-58T | 4,536 | 10,000 | 136 | Art | 4 | *3P Inplane | | | ✓ | | | |

* = Production Configuration

TABLE 1 SUMMARY OF SIKORSKY EXPERIENCE IN VIBRATION

The contract for which this report is subject, is a preliminary design study to evaluate a more advanced transmission isolation concept. In order to reduce the rotor forces transmitted to the airframe, the isolation concept currently under study is one which functions in all 6 degrees-of-freedom. The goal of this design is to provide 90% reduction in transmitted forces. Realization of this goal could mean the elimination of extraneous vibration control devices thus lowering the potential weight penalty for ride comfort and reducing the vibration portion of the flight development program to optimization of isolator tuning.

The overall purpose of the contract was to establish design requirements for main rotor isolation and to select an isolator concept which satisfies the requirements. The isolation system was to be applicable to a wide range of configurations. An appropriate helicopter model was to be selected to facilitate an evaluation of the isolation system in terms of its performance, risk, and system integration. The assessment of the system was carried out by means of parametric studies to define performance sensitivities to design parameters and the risk of achieving these design parameters. Preliminary design was carried forward to insure that the design was practical and that the details of the integration of the isolator into the helicopter system were considered. Design objectives for the isolation system were 90% attenuation of all NP main rotor shaft loads with reasonable isolation damping at a weight penalty $\leq$ 1% of design gross weight. Finally, the test demonstration program necessary to verify the proposed isolator design was to be defined. An itemized list of specific main rotor isolation design goals is shown in Figure 1.

## FIGURE 1

## MAIN ROTOR ISOLATION DESIGN GOALS

1. Functional

   - Provide 90% isolation of NP vibration at 100% $N_R$.
   - Provide not less than 85% isolation of NP vibration through upper and lower rotor speed limits.
   - Produce no system resonances at integer multiples of rotor speed - zero (or minimal) amplification of non NP vibration.
   - No amplification of 2 NP vibration (8P).
   - Provide isolation throughout the flight envelope.
   - Low static deflection - minimize shaft misalignment and control couplings for load factors up to 3.
   - No bottoming for load factors up to 2.65 (which covers the complete functional flight envelope).
   - No degradation of tuning with time.
   - Low damping in isolation units for best performance.
   - No degradation of rotor stability.
   - No degradation of aircraft Handling Qualities.

2. Structural

   - Design simplicity for improved R&M.
   - Low weight - $\leq$ 1% GW.
   - Good fatigue properties - infinite life.
   - Fail safe - failure criteria similar to those for normal gearbox mounts.
   - Single unit failure shall not;
     - Produce excessive shaft misalignments.
     - Introduce excessive control couplings.
   - System must be capable of sustaining limit load following failure of single unit.
   - Not less than 50 hrs of flight possible with single unit failed - acceptable rotor stability and handling qualities.

## 2.0 THE NEED FOR TRANSMISSION ISOLATION

Task 1 of the contract called for an evaluation of the range of rotorcraft design parameters which result in vibratory loads which make total main rotor isolation desireable. The parameters which influence vibratory hub loads are the rotor blade and hub mass and stiffness characteristics, the blade aerodynamic design, rotor/fuselage aerodynamic coupling and rotor/fuselage structural coupling (hub impedance). In addition to the helicopter design parameters, the vibratory hub loads are also strongly influenced by flight condition (airspeed, rotor speed, aircraft attitude and maneuvers). Sikorsky experience on many helicopter models has demonstrated that any of the six vibratory forces and moments may be significant to fuselage vibration depending upon the helicopter design and flight condition. For example, on the BLACK HAWK, dominant vibratory loads in cruise flight are vertical, lateral and longitudinal shear forces. In approaches, on the SEAHAWK, vertical shear load and vibratory torque are important. For the hingeless rotor ABC helicopter vibratory pitching and rolling moments are the dominant sources of vibration. While it is true that an understanding of the causes of the vibratory loads and methods of controlling them are emerging, the ability to achieve a rotor/fuselage aerodynamic and structural design with inherently low vibratory hub loads is not in hand. The concept of rotor isolation is thus an attractive alternative to satisfy near term vibration requirements.

Another factor which influences the requirement for isolation is that the resultant vibration in the airframe also depends upon the fuselage dynamic characteristics. If the resultant vibration in the airframe from an individual vibratory hub load is large compared to the requirement then isolation of that degree of freedom must be considered regardless of the magnitude of the vibratory load.

Sikorsky has extensive analytical and flight experience with the BLACK HAWK helicopter. Rotor vibratory NP loads have been calculated by both pure analysis and the use of flight measurements of hub shears and bifilar motions. Fuselage structural vibratory response has been obtained from aircraft shake testing. These data have been used to quantify the isolation needs for this aircraft. Figure 2 illustrates the study. The lower half of the figure shows the projected untreated pilot vertical 4P vibration contributions from each of the six potential rotor forces (note that the structural response to yaw is not available). The major point is that potentially any of the rotor forces could cause resultant 4P vibration above the desired levels and therefore an isolation system design should consider all 6 degrees of freedom.

FIGURE 2

BLACK HAWK VIBRATION CONTRIBUTIONS

278 Km/hr (150 Kn), 100% $N_R$, no Vibration Treatment

| | Loads From Flt Test | Pilot Vert. Mobility | Prediction (g) |
|---|---|---|---|
| $F_x$ | 3560 N (800 lb) | .025 g/1000N (.11 g/1000lb) | .09 |
| $F_y$ | 3560 N (800 lb) | .056 g/1000N (.25 g/1000lb) | .2 |
| $F_z$ | 2002 N (450 lb) | .101 g/1000N (.45 g/1000lb) | .2 |
| $M_x$ | 542 N-m(400 ft-lb) | .081 g/1000N-m(.11g/1000ft-lb) | .05 |
| $M_y$ | 542 N-m(400 ft-lb) | .081 g/1000N-m(.11g/1000ft-lb) | .05 |
| $M_z$ | 2980 N-m(2200 ft-lb) | ? ? | ? |

Projected Pilot 4P Vibration for Each Rotor Load

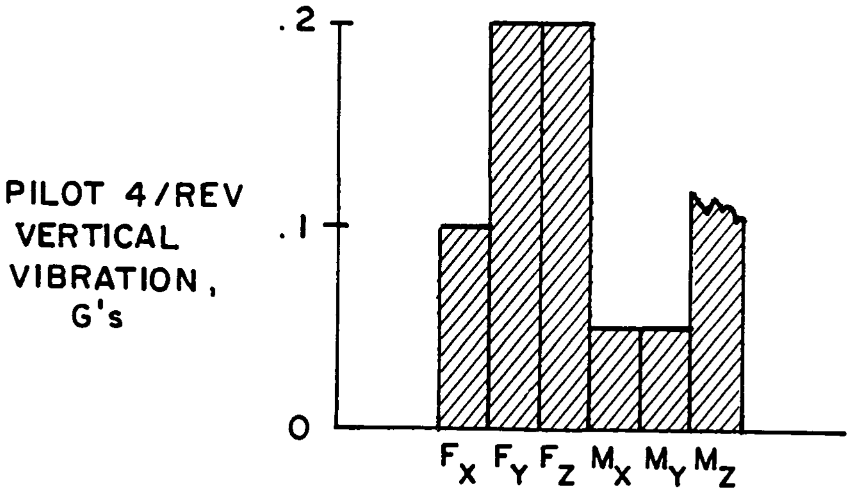


Figure 2. BLACK HAWK Vibration Contributions

The BLACK HAWK helicopter was selected as the vehicle for isolation system evaluation and preliminary design. The choice of the BLACK HAWK was based on familiarily with the dynamic characteristics of the helicopter and anticipated extensive fleet and derivatives which will develop over the next two decades. If main rotor isolation proves to be successful, improved R&M and reduction in direct operating costs for such a large fleet may provide the prerequisites necessary to make a design modification for main rotor isolation cost effective.

## 3.0 PRELIMINARY DESIGN

### 3.1 Overview

Task 2 of the contract called for an isolation system configuration study which encompassed concept selection, demonstration helicopter selection, parametric analyses to evaluate isolation system performance and sensitivities, preliminary design, and system integration. The design process necessary to accomplish this task is not one through which one can step without a certain amount of iteration. The process, shown schematically in Figure 3, represents a continuous flow of information between updated design parameters, interface deflections, and dynamic analysis to ensure system performance. These individual steps are described in the text below.

The isolation system concept chosen for evaluation is based on the concept of passive antiresonance (Reference 4). There are several characteristics that make antiresonance attractive for helicopter transmission isolation. Deflections across the isolator due to steady loads can be kept small. A fairly stiff spring can be used in the device, since a cancelling inertia force can always be obtained by proper choice of mass and lever arm. Also the system is relatively insensitive to the characteristics of the isolated body. Variations in fuselage weight can be accommodated without deteriorating the isolation effectiveness.

While the antiresonant concept is the best approach for 6-DOF isolation, there are some negative aspects of such devices. For a passive system, there is no means of opposing damping forces across the isolator, so damping must be low for effective isolation, and total isolation (zero fuselage response) is possible only with zero damping. Secondly, the system is a fixed frequency device, operating at its best at the single antiresonance frequency. Isolation deteriorates as the excitation frequency varies from the antiresonance frequency. The concept presented herein suggests the use of automatic tuning to maintain the antiresonance frequency at the NP excitation frequency of a helicopter as rotor speed or other factors vary. The antiresonance isolation device also introduces additional resonances involving the device and the bodies it connects. These resonances must be placed to avoid integer multiples of the rotor frequency and to provide adequate frequency separation from the antiresonance.

The selected configuration uses four, 2-DOF antiresonant devices, located between the transmission and airframe and arranged to provide system isolation in all 6 degrees-of-freedom. The individual units, shown in Figure 4, consist of a rod of circular cross section with a diameter which is tapered as a function of length. This rod is attached to the fuselage at two

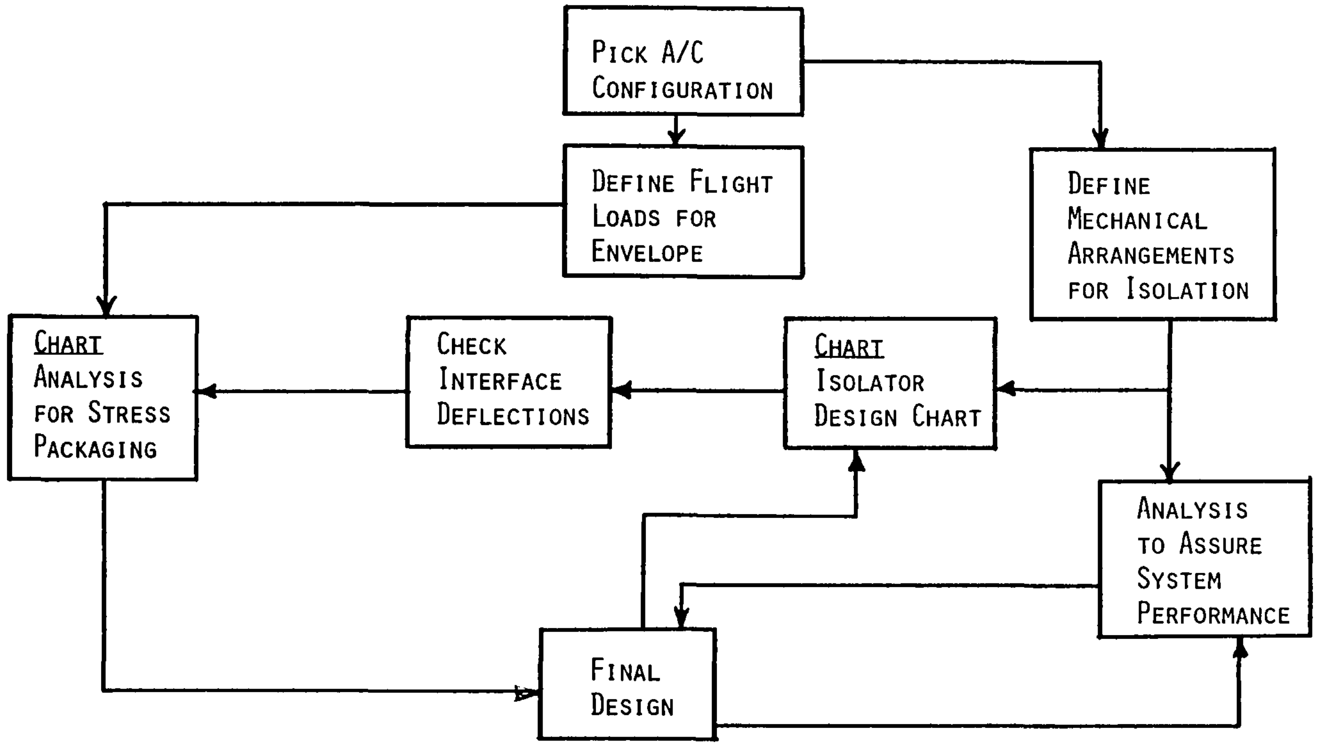


Figure 3. Design Process for Isolation System.

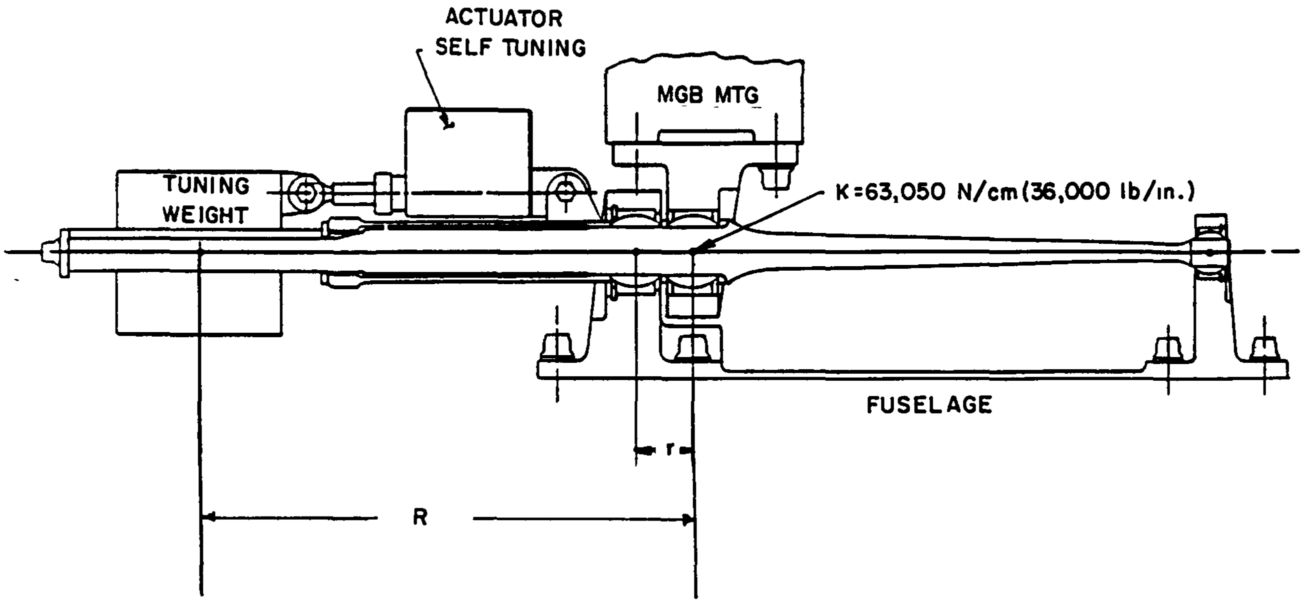


Figure 4. Two Degree-of-Freedom Isolator.

points and connected to the transmission at a single point. The overhanging end of the rod has an attached weight which is the dynamic mass of the antiresonant device. The section of the rod between the two fuselage supports is flexible and serves as a stiff spring between the fuselage and transmission. Spherical bearings are used at all attachment points and the circular cross section of the isolator gives it the same characteristics in both transverse axes. Therefore, the isolator responds in two degrees of freedom. The use of springs with little hysteretic damping and few components provide a system with low damping.

Another essential feature of this isolator is its axial freedom. For use in combination to provide 6-DOF transmission isolation, the individual isolation units must be unrestrained axially. This freedom can be achieved in a number of ways, Figure 5. The spherical bearing attaching the transmission to the isolator can be mounted so that it is free to slide relative to the transmission foot. Alternatively, an elastomeric bearing or a flexible diaphragm could be used.

Provision for automatic variable tuning of the isolator is shown in Figure 4. An electric actuator can be used to vary the mass location to maintain the antiresonance with varying NP frequency excitation. This device is only conceptual and no sizing or weight penalities have been established.

A plan view of a 6-DOF isolation system arrangement with four units is shown in Figure 6. Vertical forces on the transmission are reacted by vertical motion of all four isolators. Yaw excitation is reacted by inplane motion of all four isolators. Inplane forces (lateral and longitudinal) are reacted primarily by inplane motion of opposite pairs of isolators. Pitch and roll excitations are reacted primarily by vertical motion of all four isolators (Figure 7). Note that all steady loads are reacted by the rods. The choice of a fairly high stiffness value keeps the steady deflections low.

The isolation system arrangement (shown in Figure 6) requires interaction among a multiple number of units for any degree-of-freedom. Because of this coupling among various degrees-of-freedom, the effectiveness of the isolation system can only be evaluated by an analysis which takes into account all four isolators and the dynamics of the rotor, transmission, and airframe. A discussion of the analysis and the results obtained which substantiate the effectiveness of the proposed system is given below.

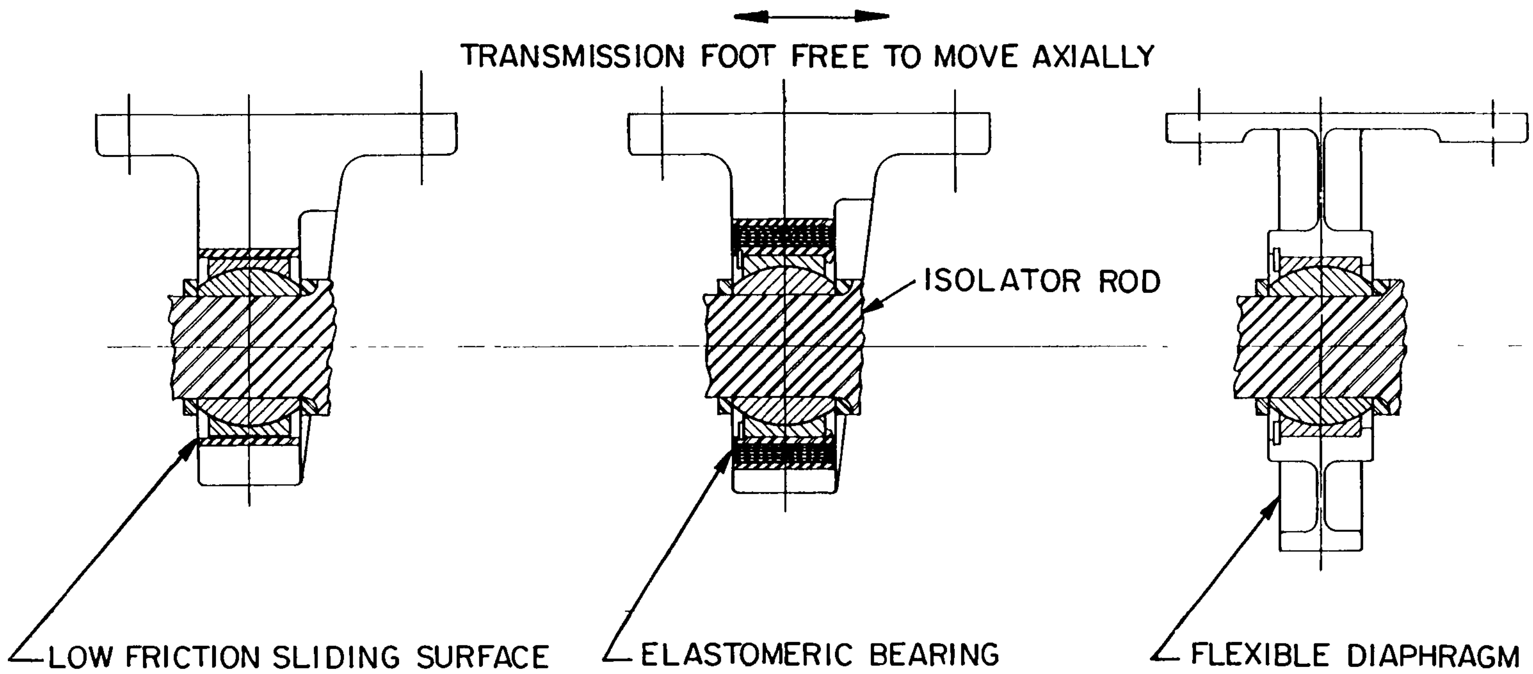


Figure 5. Methods for Obtaining Axial Freedom.

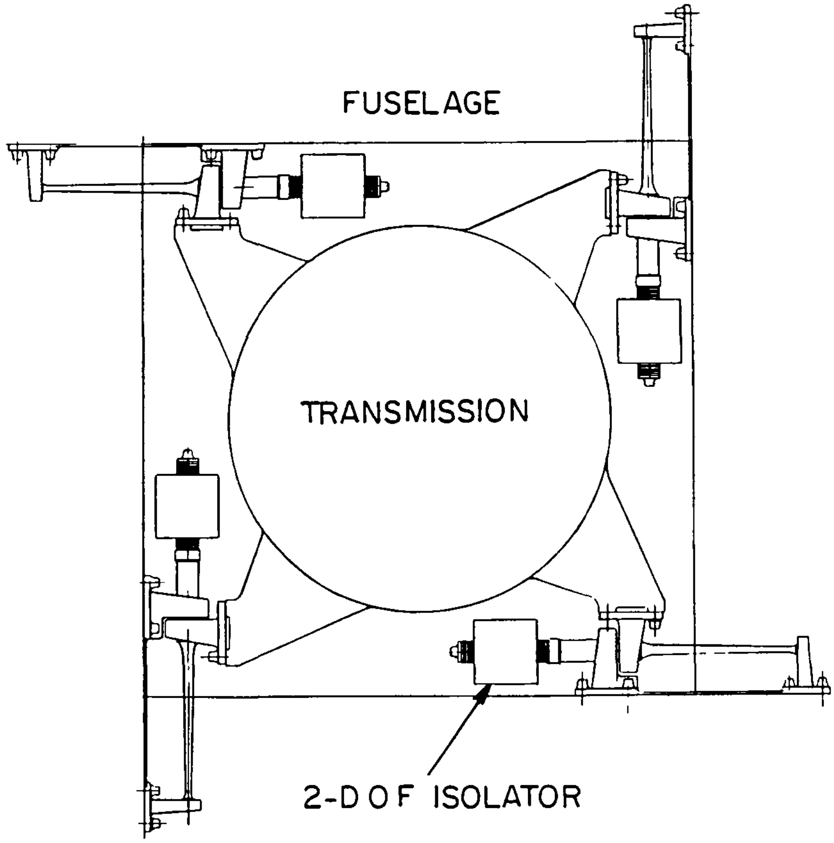


Figure 6. Six Degree-Of-Freedom Isolation System Installation.

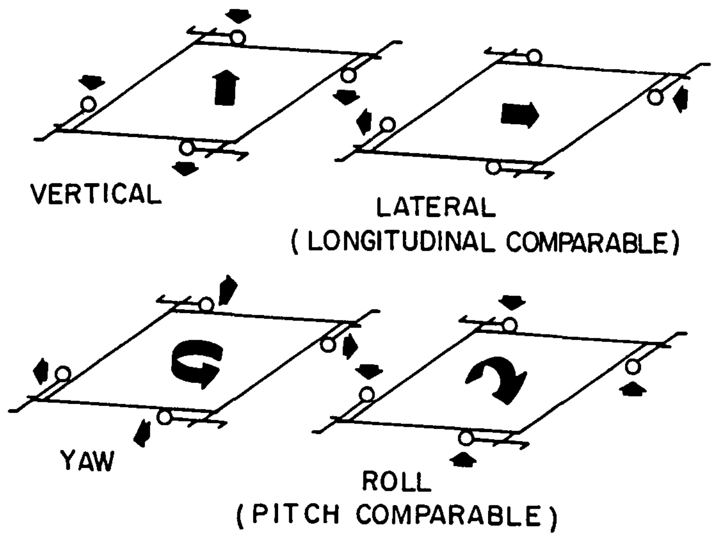


Figure 7. Principal Isolator Responses to Loads.

## 3.2 Coupled Rotor/Transmission/Isolation/Fuselage Analysis

The mathematical model for the Coupled Rotor/Transmission/Isolator/Fuselage Analysis is shown schematically in Figure 8. The rotor is represented by a 12 x 12 impedance matrix which is either input or calculated internally using eight coupled blade modes. The rotor is attached to the transmission which is modeled by up to ten modes. The transmission rests on up to five isolator units which can be located arbitrarily. These isolators sit on the fuselage airframe which consists of up to sixteen modes. Rotating absorbers can be attached to the hub, and fixed absorbers can be attached to the fuselage.

The computer analysis uses a modular structure. Each module is coupled to the upper (above the isolators) or the lower (below the isolators) body through the mode shapes that describe the motions of the connecting points. As shown in Figure 9, each module is added as an impedance matrix in terms of upper and lower body DOF's. The size of the impedance matrix remains constant even though many degrees of freedom are added. The rotor impedance is then added simply in terms of upper body degrees of freedom. Because the size of the matrix does not increase with the added degrees of freedom, computer core requirement is small and computing time is also very small.

Figure 10 shows the details of the mathematical model of the isolator unit. The unit is an antiresonant device which can be defined to give isolation in three directions. The unit has three-directional flexibility at the isolator attachments to the upper and lower bodies and the dynamic mass support arm can be made flexible. Rotary inertias of the dynamic masses of the isolators are also included.

Up to six forcing functions are input at the main rotor hub with amplitude, phase, and frequency. In addition, the program will accept excitations at locations other than the main rotor hub, so that interaction of all excitations can be evaluated. Automatic plotting of the forced responses of the main rotor hub, individual isolator attachment points, and any points on the fuselage where mode shapes are specified, is available and enables rapid parametric variation study.

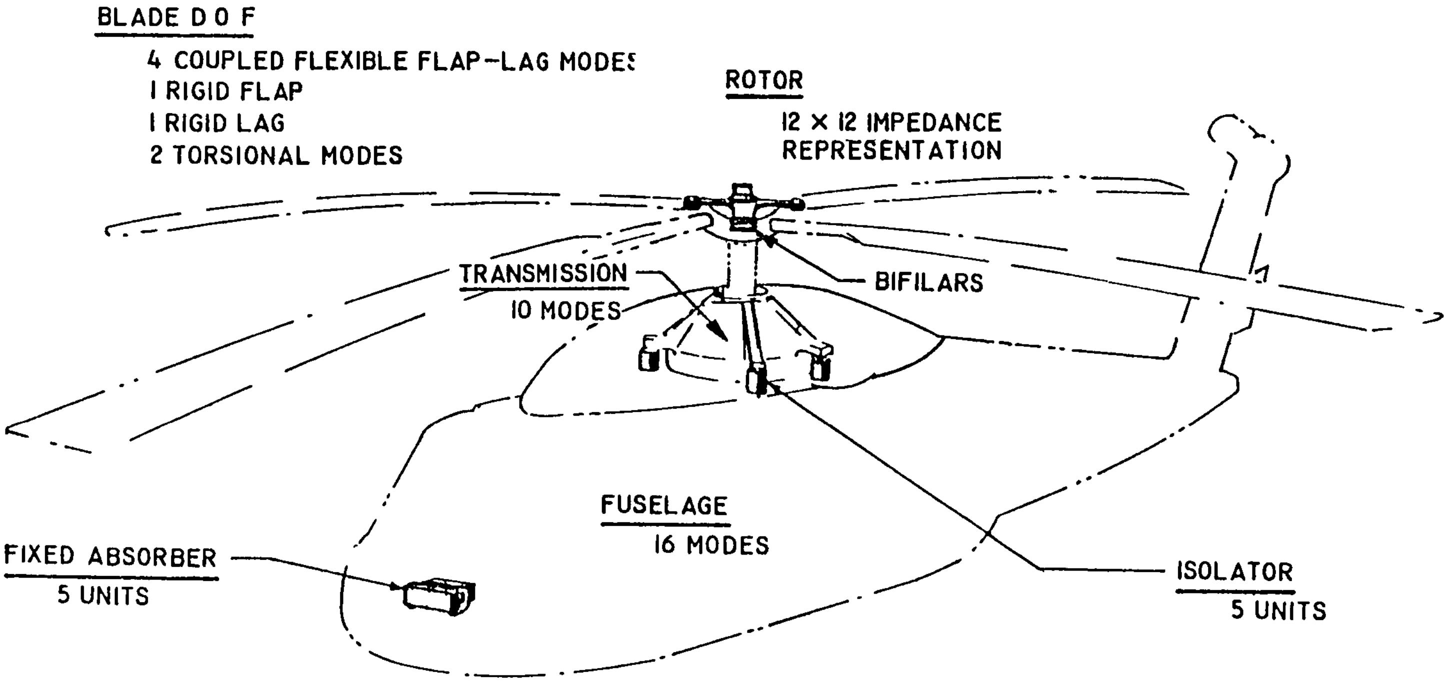


Figure 8. Mathematical Model Used in Analysis.

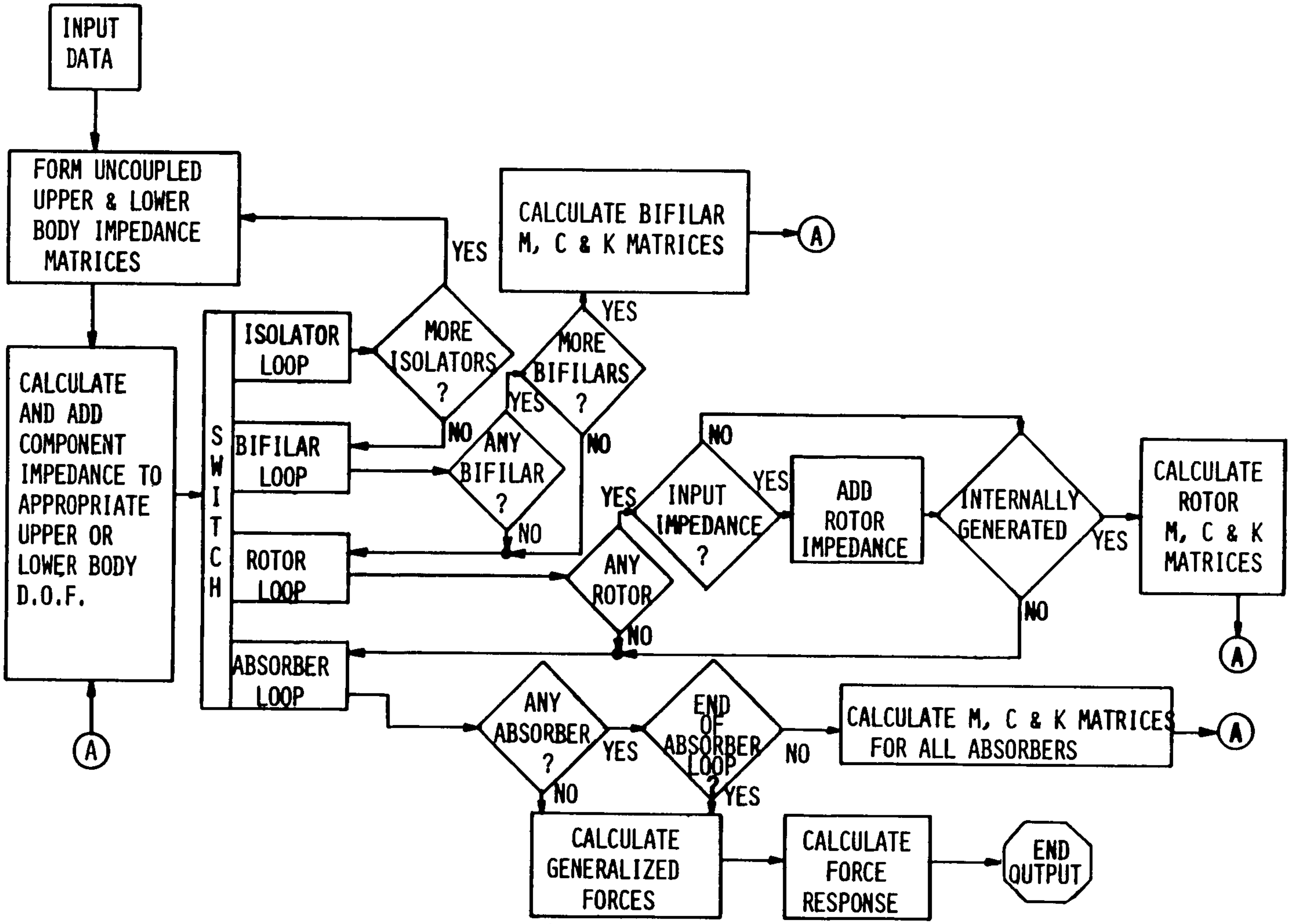


Figure 9. Flow Diagram of Analysis.

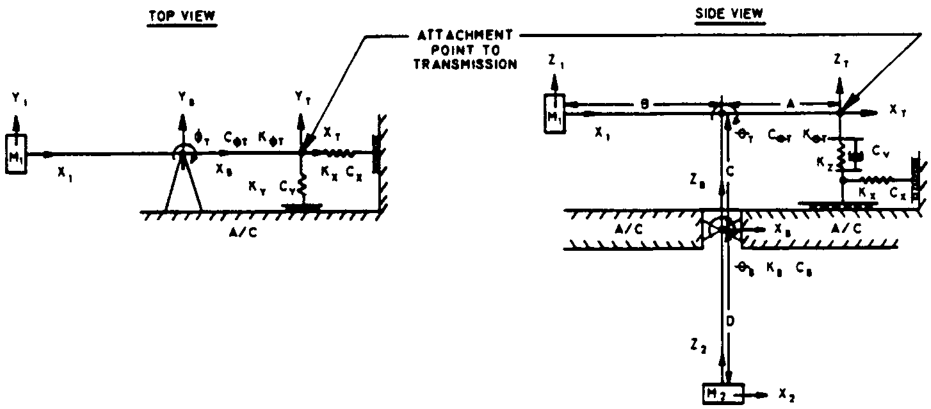


Figure 10. Mathematical Model Isolator Unit.

### 3.3 Analytical Studies

The isolation system analysis has been used to evaluate a number of transmission isolation concepts. The analytical study of the concept being proposed, Figure 11, has included a number of different configurations for installation on a BLACK HAWK helicopter. The figure shows a schematic of the bar type design of the two degree of freedom (DOF) isolator (self tuning feature not shown). For the configurations studied only the isolator stiffness and dynamic mass were varied. It is recognized that variation in the waterline placement of an isolation system relative to the upper and lower body cg's can give certain dynamic advantages. Such variations were not studied here because the system waterline was dictated by the existing aircraft configuration and the liberty of varying this parameter was restricted.

A major advantage of this type of 2 DOF isolator design is that its effectiveness and the frequency location of its maximum isolation point is dependent on the fixed design parameters of mass arm lever ratio, spring stiffness and dynamic mass, and insensitive to configuration changes of the lower body. Thus, the isolator performance is virtually insensitive to aircraft gross weight and center of gravity variations. A simple rigid mass dynamic model yields the equation

$$\omega_a^2 = \frac{K}{M_D\ (R/r - 1)\ R/r}$$

where $\omega_a$ is the antiresonant frequency. The requirement of placing this frequency at the aircraft principal excitation frequency, four times main rotor speed (4P), defines a relationship between isolator weight $M_D$, isolator stiffness K, and the mass arm lever ratio R/r. The family of possible design solutions for the BLACK HAWK aircraft is shown in Figure 12 which shows a collection of curves whose antiresonances all fall on 4P.

The solutions show that any decrease of R/r or dynamic mass to meet size or weight requirements will require an appropriate reduction of isolator stiffness to maintain maximum isolation of 4P transmission motions. Also shown are the three isolator configurations that were studied in detail and are presented in this discussion. A rigid body transmission, rigid body fuselage, and a rotor impedance model were used for the analytical studies.

An effective six DOF isolation system was found for a total system weight of about 1% of aircraft gross weight 7.71 kg (17 lb) dynamic mass per unit and an isolator stiffness of 63,050 N/cm (36,000 lb/in). For this baseline configuration, (and with a rigid airframe model) Figure 13 shows that minimal fuselage response can be obtained at the 4P antiresonance for a two percent

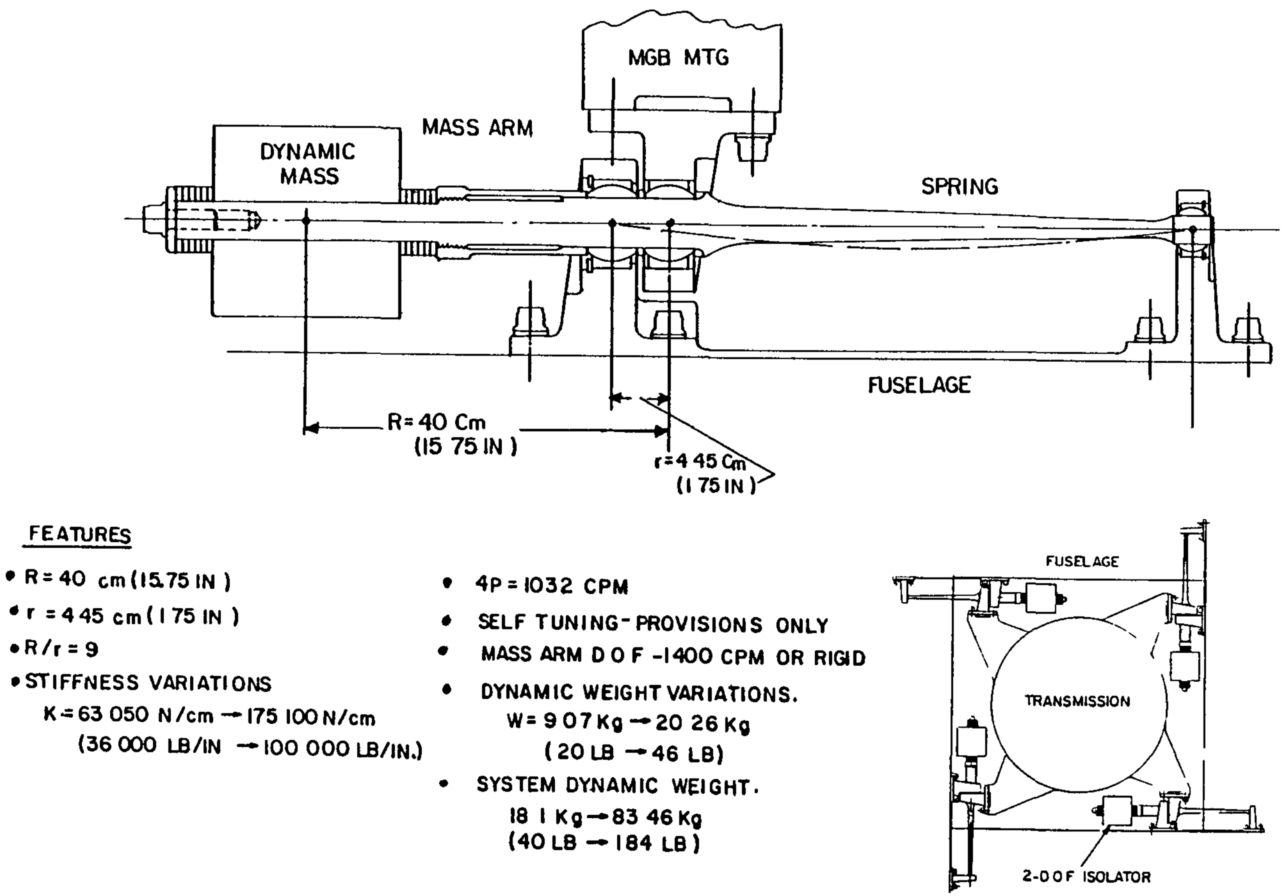


Figure 11. Sketch of 2 DOF Isolator Unit.

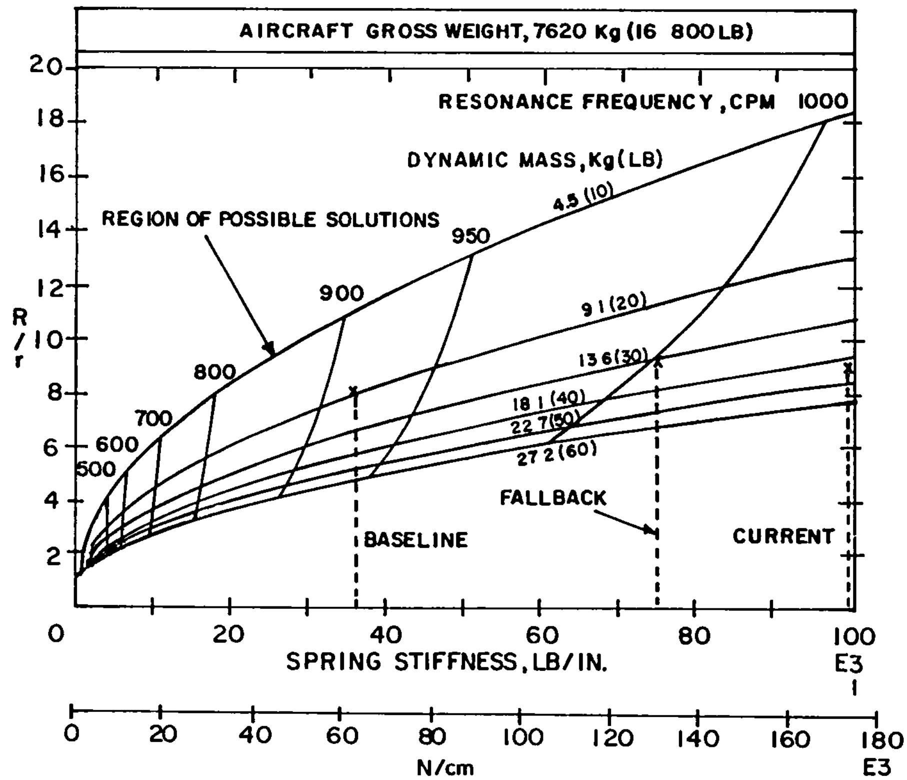


Figure 12. Isolator Spring Design Chart.

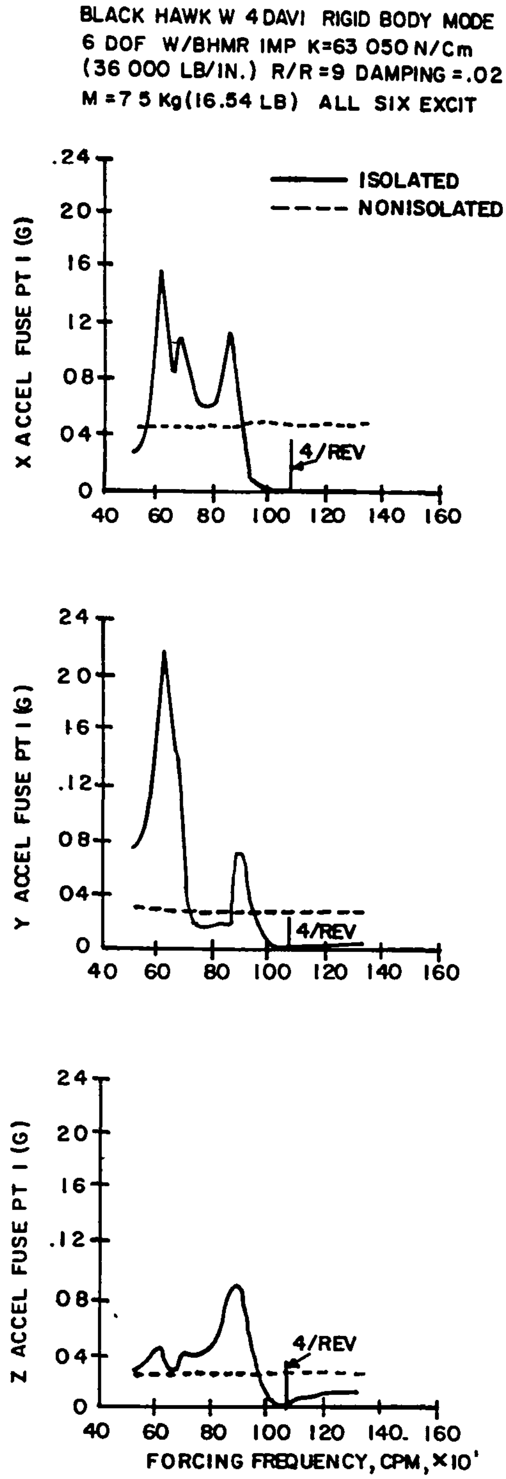


Figure 13. Forced Response For the 6 DOF Isolation System.

damped isolator system. Response is shown in three axis at the aircraft c.g. (fuselage Pt. 1) for simultaneous excitation of three rotor forces and three rotor moments. These rotor excitations are representative of the BLACK HAWK aircraft at 278 km/hour (150 kts) and a gross weight of 7620 kg (16,800 lb). The rotor excitations are: 3560 N (800 lb) for lateral and longitudinal, 2002 N (450 lb) vertical, 542 N-m (400 ft-lb) rolling and pitching, and 2980 N-M (2200 ft-lb) yaw. As expected, minimal 4P response was also calculated for all three axes at the attachment of each isolator to the airframe. With the isolators blocked out the analysis shows that the aircraft c.g. response is at least ten times larger. The variations shown in the rigid body longitudinal (X) and lateral (Y) fuselage c.g. response with forcing frequency is a coupled effect of the main rotor head impedance. For the vertical response the rotor head impedance shows little effect.

Reduction of isolator bar design to practice was accomplished by applying maximum isolator loads resulting from main rotor head steady forces and moments for all aircraft flight conditions. These loads will determine the feasibility of the isolator configuration. The BLACK HAWK flight envelopes are shown in Figure 14. The structural envelope represents all flight conditions for which the aircraft structure is designed. The aerodynamic envelope describes flight conditions which have been flight test demonstrated.

The operational maneuvering (functional) envelope represents flight conditions comprising over 99.9% of the BLACK HAWK mission profile (Figure 15). Flight conditions, both level flight and maneuvers, were selected from the mission profile and run through the Sikorsky flight simulator. The resulting rotor head forces and moments, and aircraft accelerations were than used to generate the envelope.

The degree of conservatism in designing the isolation system to this functional envelope is demonstrated in Figure 15. As shown, this envelope of 2.65 g's at 120 kts (from Figure 14) covers more than 99.9 percent of the mission profile of the BLACK HAWK and SEAHAWK aircraft. Applying the rotor head loads and motions from the functional envelope resulted in a worst case design load of 77,840 N (17,500 lb) load at one isolator. In all cases the loads at the other three isolators were less because of the phase (cancellation) effect of each isolator load due to the three rotor forces and three moments. The particular isolator that experiences the maximum load varies with each flight condition, therefore the maximum load is used to design all four isolators. To add more design conservatism, the criteria were established that each isolator would be designed to an even higher steady load of 89000 N (20,000 lb) and a vibratory load of ±13,350 N (±3000 lb) before the isolator bottoms out.

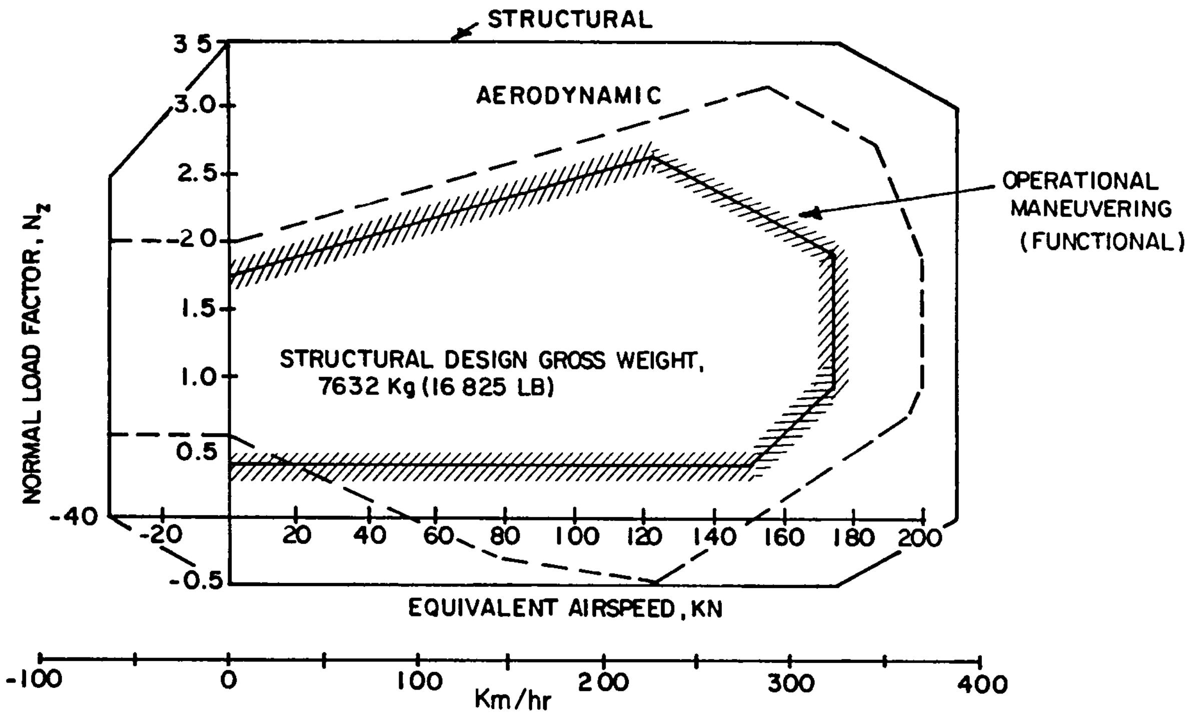


Figure 14. V-Nz Diagram, Sea Level, Standard Day.

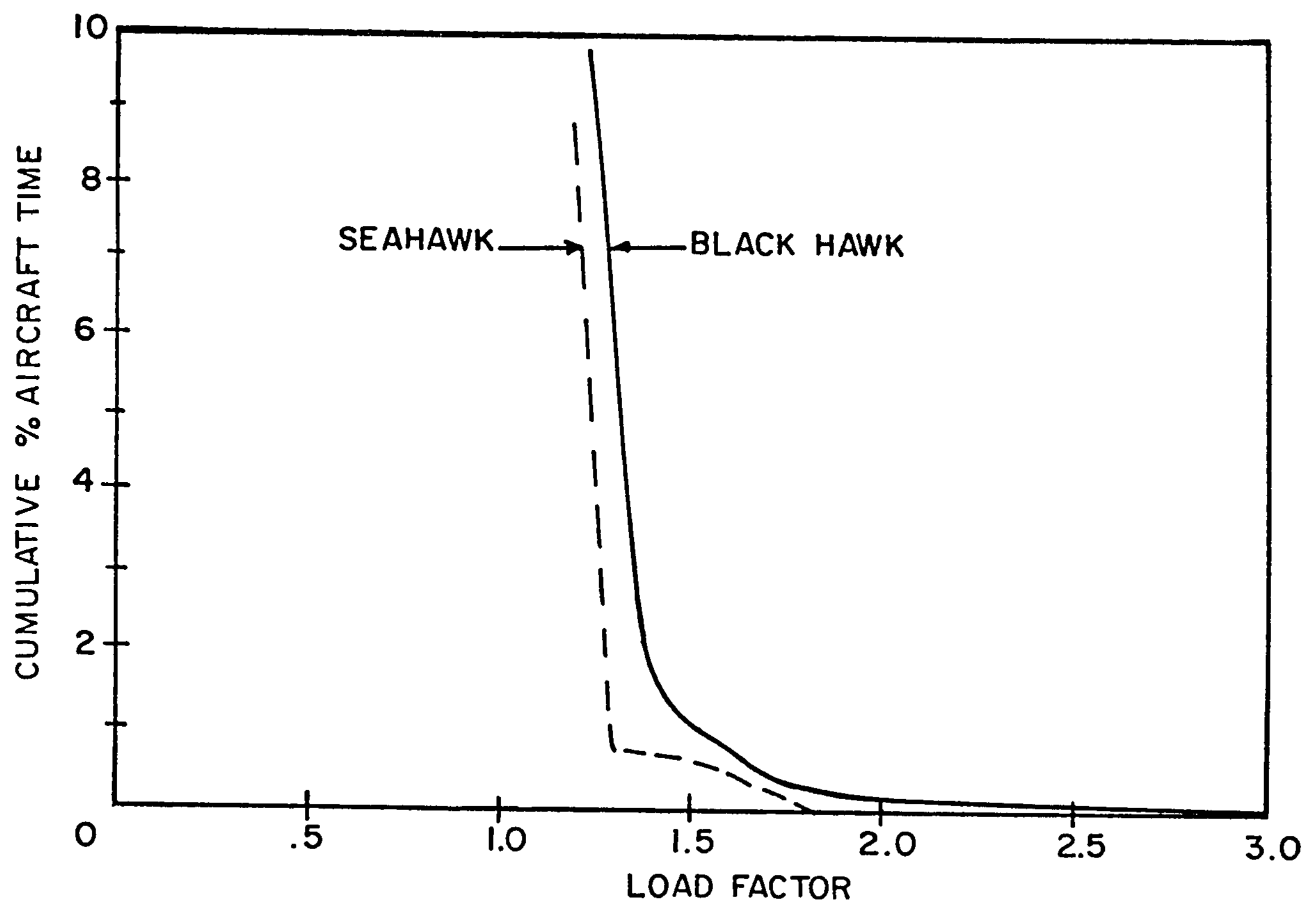


Figure 15. BLACK HAWK/SEAHAWK Mission Profile.

Using these design loads, the isolator baseline configuration [K = 63,050 N/cm (36,000 lb/in] would not meet the infinite life criteria, (Figure 16). As shown, the maximum bar stress calculated for the design loads significantly decreases as the isolator spring rate is increased. The minimum stiffness required for infinite life is 131,400 N/cm (75,000 lb/in). For all isolator configurations a tapered cross section of the bar has been used to reduce the maximum stress.

In practice all isolator configurations will have infinite life and a fail safe feature by allowing the isolators to deflect only to the point where the maximum allowable stress is encountered, after which the units bottom out and the additional load is carried through a load path external to the isolator spring. Figure 17 shows how the design allows bottoming and provides a fail safe condition even in the event of a spring failure. With the isolator bottomed, the backup structure will provide the required load path to handle the loads that develop beyond the isolator design envelope, but within the aircraft structural envelope.

To conservatively provide operation of all four isolators for no bottoming within the functional envelope, the isolator stiffness was raised from 63,050 N/cm to 175,100 N/cm (36,000 to 100,000 lb/in) and a corresponding dynamic mass of 20.9 kg (46 lb) 83.5 kg (184 lb) dynamic weight = 1.1% DGW). Figure 16 shows that for this current configuration the calculated maximum bar stress is well below the allowable. To still maintain the design goal of one percent gross weight for total isolator system weight, the isolator dynamic mass had to be reduced. By dynamically amplifying the mass motion by making the rigid support shaft flexible, the mass could be reduced from 20.9 kg (46 lb) to 9.07 kg (20 lb). Figure 18 shows that tuning this cantilever 9.07 kg (20 lb) mass to 1400 cpm will provide the same aircraft isolation as the 20.9 kg (46 lb) mass. This approach appears quite attractive, however when one calculates the physical parameters necessary to give a 9.07 kg (20 lb) weight/bar mode at 1400 cpm, the diameter comes out quite small and creates a stress problem. Therefore the flexible arm approach has been discontinued. Reducing the system mass can now only be accomplished by reducing the bar stiffness. The remainder of the work was performed with the assumption of a rigid mass arm.

To gain a basic understanding of how the different isolator physical parameters effect the isolator load capability for the applied forces from flight loads, a design chart was generated (Figure 19) based on a simple pinned-pinned beam with a constant cross section which approximately represents the current isolator design (stiffness of 175,000 N/cm (100,000 lb/in). As shown, the isolator load capability can be increased by increasing the

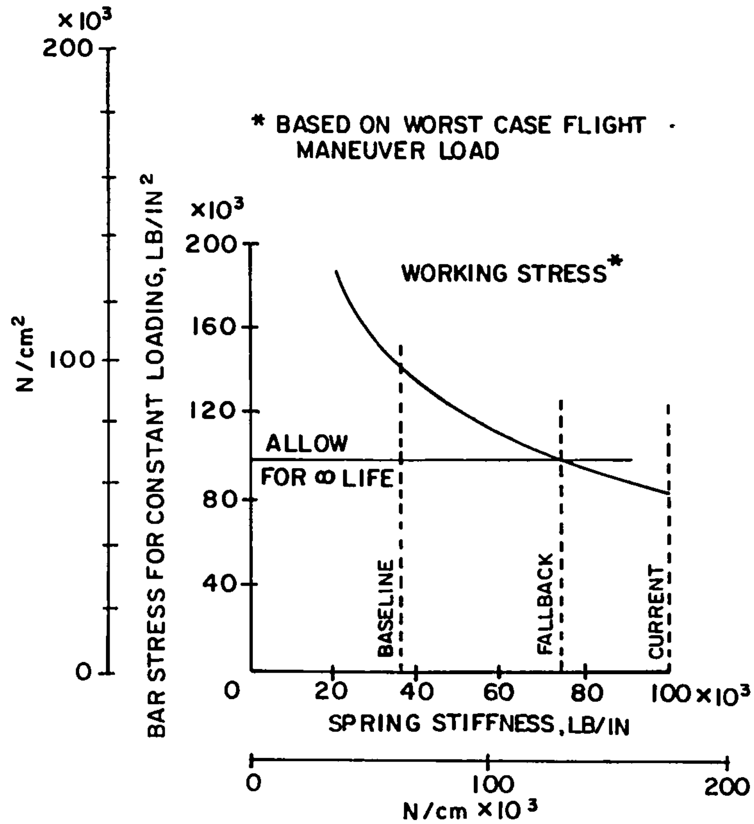


Figure 16. Spring (Bar) Stress as a Function of Stiffness.

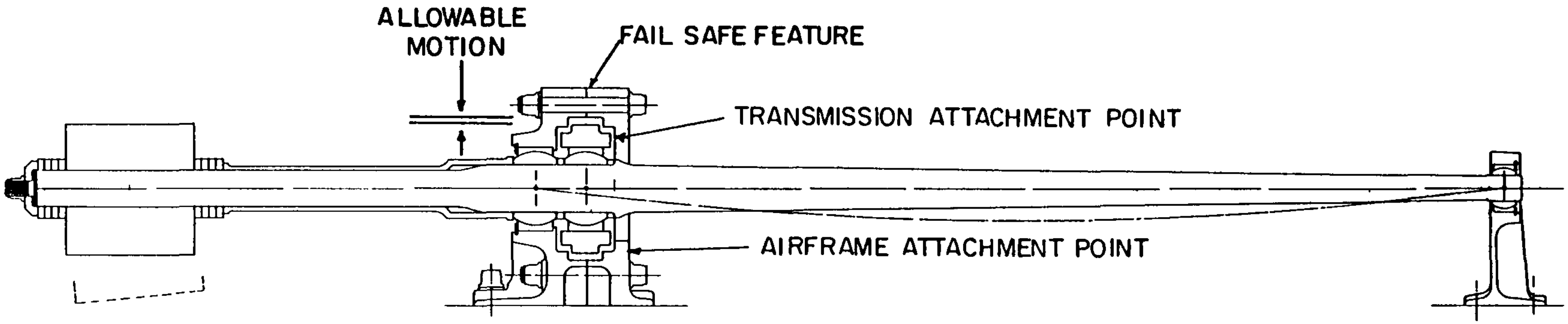


Figure 17. Two DOF Isolator Showing the Fail Safe (Capture) Feature.

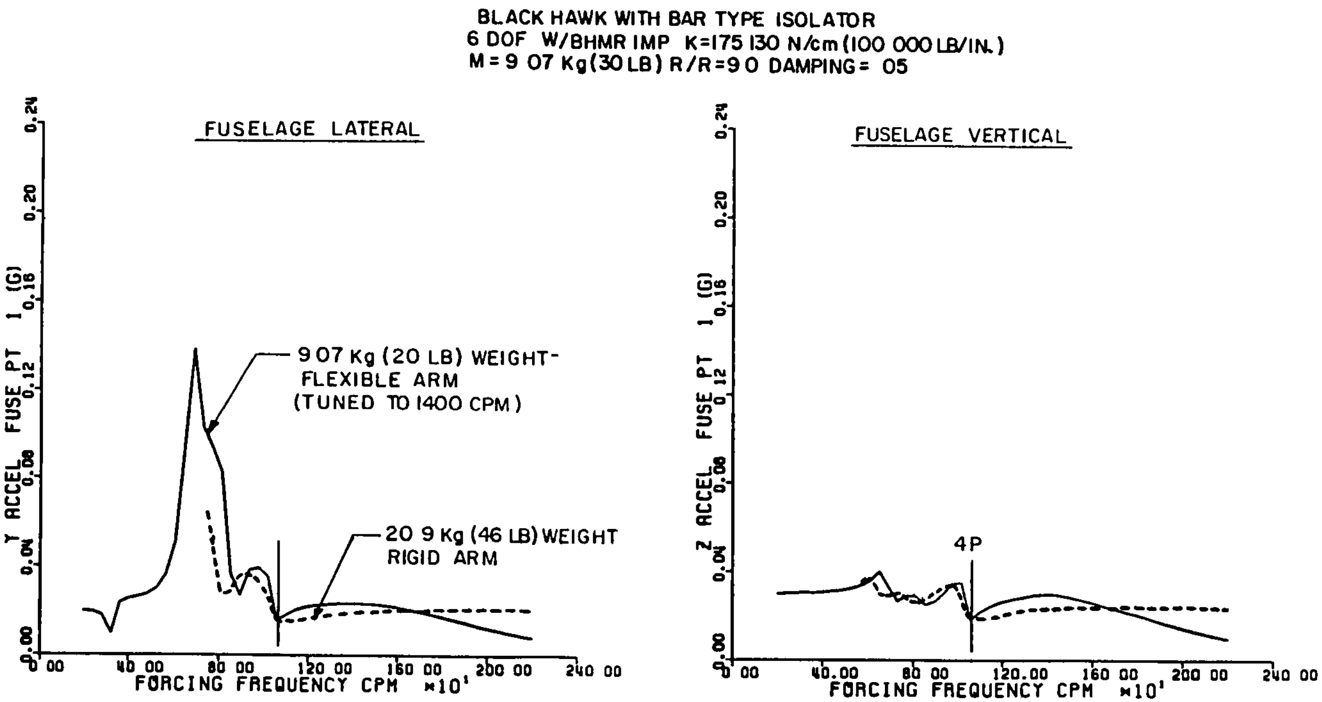


Figure 18. Comparison of Rigid/Flexible Mass Arm.

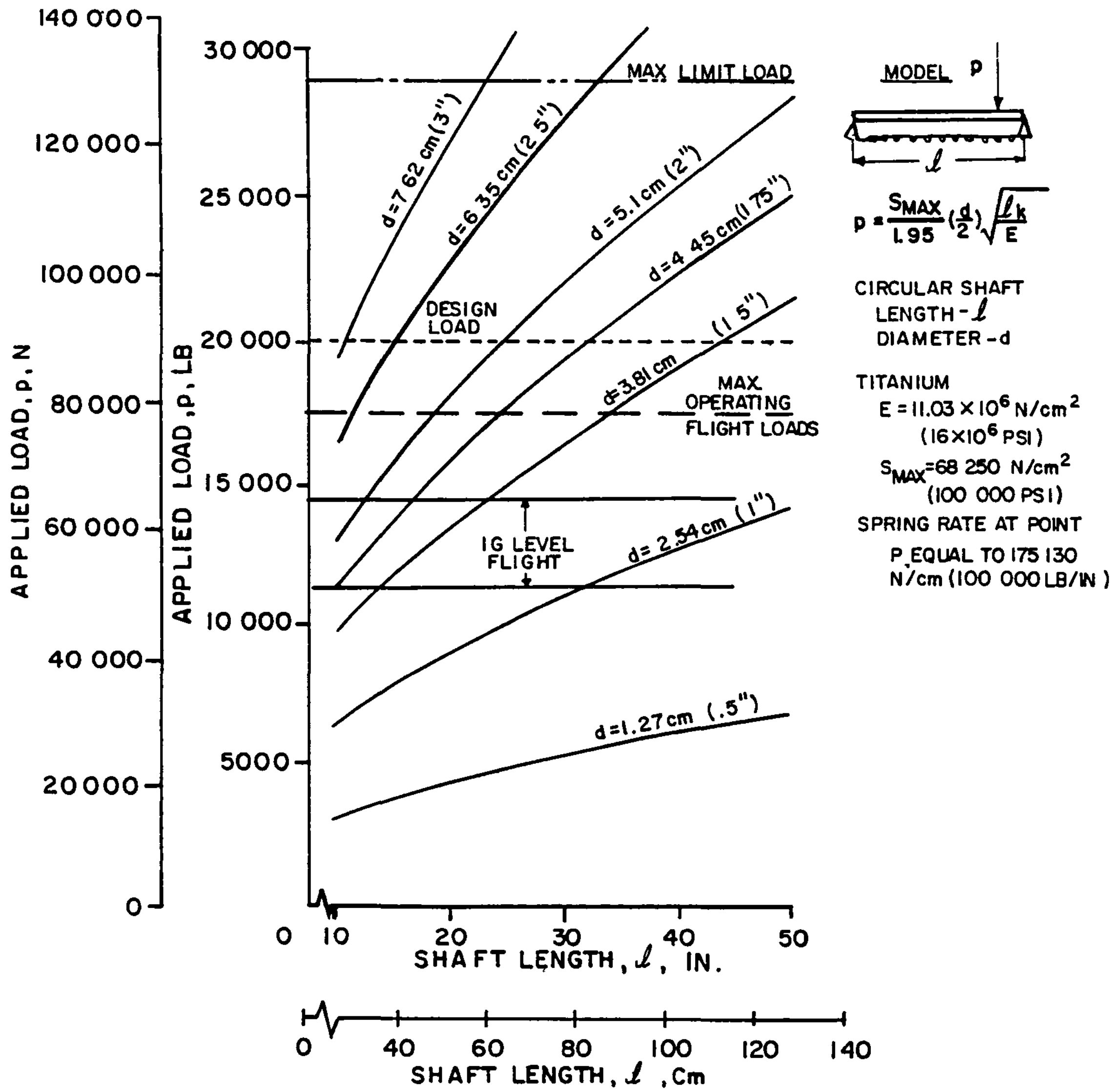


Figure 19. Design Chart for Detail Sizing of Current Spring Bar Configuration.

distance between the aircraft attachment points and/or increasing the shaft diameter. Bearing size and aircraft fit, will limit the extent to which these parameters can be increased. For the current isolator configuration, a computer stress analysis showed that a basic shaft diameter of 4.13 cm (1.625 in) with a cross section taper of .024 cm/cm (in/in) and a shaft length of 83.82 cm (33 in) would satisfy the stress requirements.

As a tradeoff of isolator performance (percent isolation) within the operational envelope (no isolator bottoming), a fall-back configuration of isolator stiffness of 131,400 N/cm (75,000 lb/in) and dynamic mass of 15.65 kg (34.5 lb) [62.6 kg (138 lb) dynamic weight = 0.82% DGW] is presented. This configuration represents the lowest isolator stiffness that would yield a predicted infinite life, (see Figures 12 and 16) which, in practice, requires no bottoming of the isolator for loads within the functional flight envelope.

For the three isolator configurations, the aircraft c.g. response was compared with and without isolators to determine percent isolation of the airframe for the rotor with all six vibratory excitations. Figure 20 shows the percent isolation for the rotor speed range of 98 to 102% $N_R$. As shown, the isolator with the lowest stiffness [63,050 N/cm (36,000 lb/in)] provides the highest percent isolation at all rotor speeds and the least reduction of effectiveness as rotor speed is varied from 100% $N_R$. However, because of the stress picture already discussed, the isolator configurations with higher stiffness must be considered. The percent isolation and its variation with rotor speed for the stiffer isolator configurations can be improved by lowering the inherent damping of the system. Figure 21 shows again the percent isolation of the three isolator configurations but with the damping lowered from 2% to 1% critical. Comparison of the two figures show that percent isolation was significantly improved by lowering system damping. For example, the isolator configuration with stiffness of 131,400 N/cm (75,000 lb/in) had its average percent isolation raised from 83% to just over 90%. The final system, when designed, is expected to exhibit 1-2% critical damping depending on the type of bearings used and the degree-of-freedom addressed.

The analytical studies have demonstrated that the proposed isolation systems will work for all six degrees-of-freedom and will meet the design goals for more than 99% of the BLACK HAWK mission profile. The total isolator effectiveness can be further increased by incorporating a self-tuning feature into the isolator design. This would match the antiresonant frequency of the isolator to NP as the rotor speed is varied and would provide over 90 percent isolation at all normal operating rotor speeds. The feedback loop for this self tuning feature could either be open

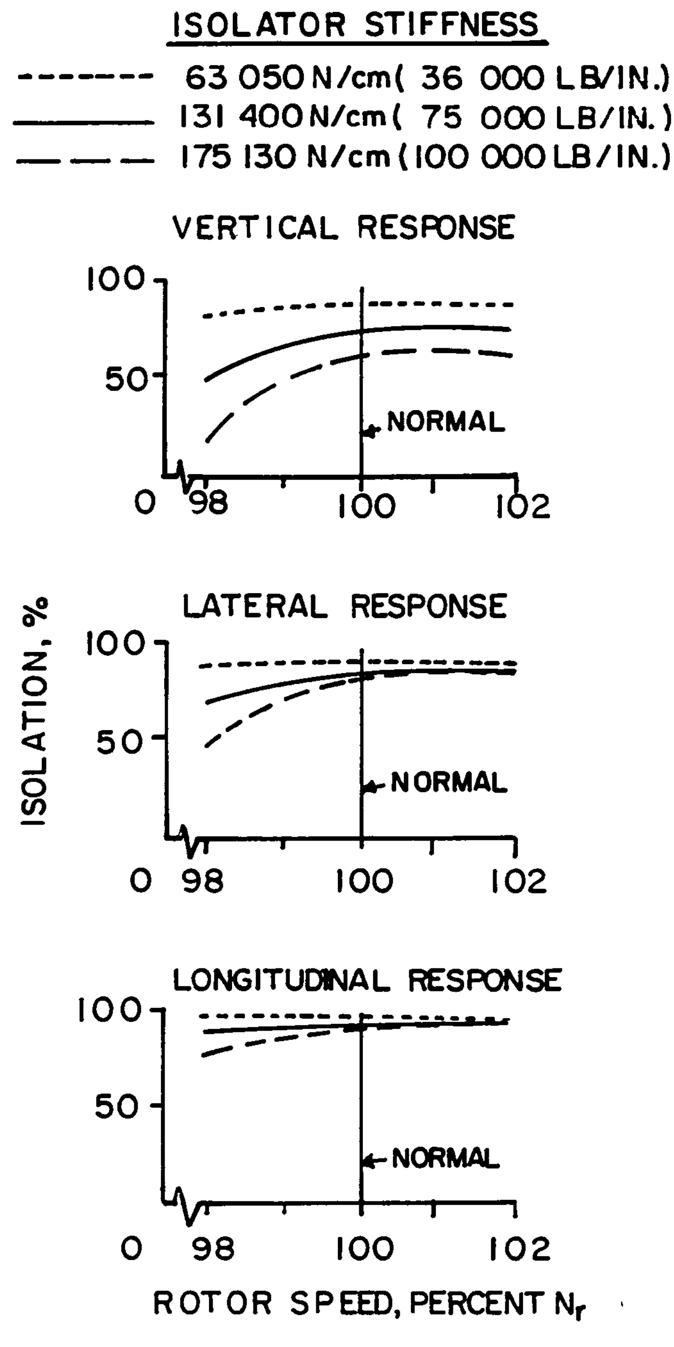


Figure 20. 4P Isolation System Effectiveness - 2% Damping.

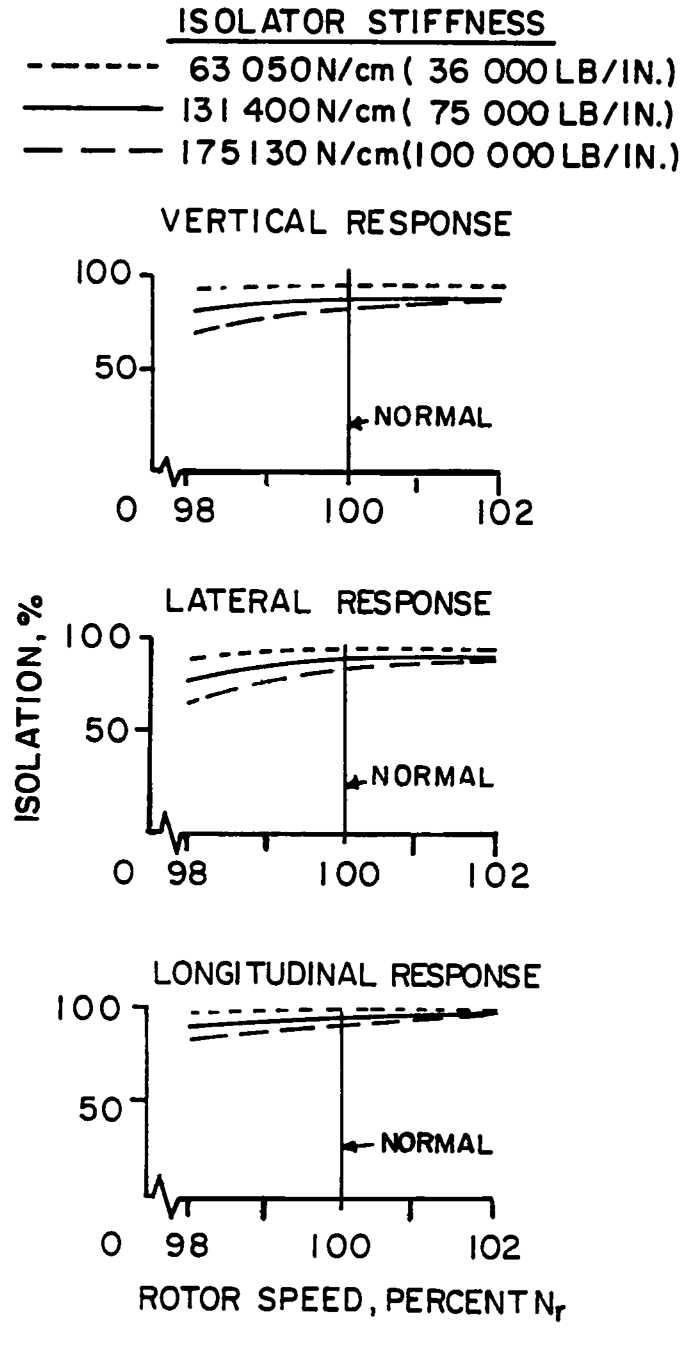


Figure 21. 4P Isolation System Effectiveness - 1% Damping.

loop rotor RPM control or closed loop null (bucket) sensing control. Either way, the self-tuning feature would allow an easy input of bias control to optimize the tuning configuration during flight. Again, this self tuning feature is conceptual and no weight penalties have been estimated. The actuator device, however, could be configured such that it would become part of the isolator dynamic mass thus decreasing its penalty on the total system weight.

## 3.4 System Integration

Integration of the isolation system into the aircraft is perhaps the most difficult aspect of the design phase. Establishing isolator design parameters such as stiffness and strength is but the beginning of the full effort - making it fit into the airframe and act in harmony with the other aircraft subsystems becomes a significant task. This task is easier when performed in parallel with the detail design of a new aircraft model due to the flexibility of the airframe and transmission design disciplines. When, however, the aircraft is already built and in production the integration process becomes quite difficult due to the loss of this interdesign discipline flexibility. The isolators must now be made to fit within an existing envelope with the least number of alterations. Such is the situation here. The basic guideline set forth at the outset of the isolation system airframe integration is that the locations of the rotor head, engines, and all shafting intersections with the main transmission would remain unchanged. Under these restrictions, the waterline of the isolation system becomes virtually fixed. In this manner, the integration is confined to the transmission housing, local airframe structure, drive shaft couplings and control system interface points.

As currently designed, the main gearbox bolts directly to the aircraft transmission beams on the left and right sides, and to lateral cross members fore and aft. Insertion of the isolators will require space allowance between these members, potentially requiring redesign of the transmission housing, the airframe structure, or both. Preliminary design indicates that the airframe members will have to be relocated away from the transmission centerline, i.e. the transmission beams moved outboard and the lateral cross members moved forward (for the fore member) and aft (for the aft member). In addition, the transmission housing will need to be redesigned to relocate the feet and ribs so they may interface with the isolator and new airframe structure. A preliminary design sketch of the installation is shown in Figure 11.

Due to the increased motion of the gearbox in the isolated configuration, motions across critical interface points become of concern. The translations and rotations of the transmission relative to the engine and tail takeoff shafts become important from the standpoint of coupling life. Equally important are the relative deflections of the points at which the rotor controls cross the airframe/transmission interface. Situations in which motions of the gearbox generate inputs to the control system must be avoided both from handling qualities and stability viewpoints.

Misalignments of the drive shaft couplings were calculated from motions resulting from a worst case limit load condition. The rotor loads used were generated on the simulator and represent a rolling pullout - right at 105 kt and 125% rotor speed ($N_Z$ = 2.83). The resulting deflections at the drive shaft/transmission couplings for both the 175,130 N/cm (100,000 lb/in) and 131,400 N/cm (75,000 lb/in) cases are shown in Table II. The maximum allowable shaft misalignment for a single Thomas coupling pack in a transient condition is approximately 1.0°. The resultant angles developed by this limit load condition are shown at the bottom of Table II. It can be seen that the engine couplings are well within this envelope for both the 175,130 N/cm (100,000 lb/in)and 131,400 N/cm (75,000 lb/in) configurations. The tail takeoff coupling, however, is beyond the operational limit and will require a redesign. The engine/airframe mounting configuration allows the engine to move in all degrees-of-freedom except roll (made possible by small rotations at the engine rear mount trunions), thus making them quite forgiving to transmission motion. The tail shaft, however, is more restricted. The first airframe bearing allows the shaft angular freedom, but is quite restricting in the axial direction. This compounds the problem in that not only is the coupling out of angular misalignment tolerance, but it will not tolerate the axial (longitudinal) motion of the transmission. The redesign, therefore, will require a crowned spline type arrangement.

Handling qualities, like vibration, is one of the aircraft attributes most noticed by the pilot. Motions of the isolated transmission relative to the airframe for the limit load case discussed above will generate inputs to the rotor control system on the order of 2% cyclic and 4% collective for the 175,130 N/cm (100,000 lb/in) configuration and 3% cyclic and 5% collective for the 131,400 N/cm (75,000 lb/in) case. These inputs are felt to be unacceptable, therefore making it necessary to design control system linkages which will compensate for all six degrees-of-freedom of transmission motion.

The BLACK HAWK has the control system primary servos mounted on the airframe upper deck rather than on the gearbox, thus the servo outputs must traverse the interface. The problem which must be dealt with now is one of compensating high magnitude servo loads rather than low level servo input loads which one would normally have on an aircraft with the servos mounted directly on the transmission.

## TABLE II CRITICAL INTERFACE DEFLECTIONS

Flight condition: Rolling pullout-right 195 km/hr, (105 kt), 125% rotor speed ($N_Z$ = 2.83)

Rotor Forces (+aft, right, up)

INTERFACE DEFLECTIONS

| | K-(SPRING ROD) | |
|---|---|---|
| | 175,130 N/cm (100,000 lb/in) cm(in) | 131,400 N/cm (75,000 lb/in) cm(in) |
| **No. 1 Engine Input** | | |
| Longitudinal | -0.406(-0.160) | -0.541(-0.213) |
| Lateral | -0.015(-0.006) | -0.020(-0.008) |
| Vertical | -0.147(-0.058) | -0.196(-0.077) |
| **No. 2 Engine Input** | | |
| Longitudinal | 0.249( 0.098) | 0.333( 0.131) |
| Lateral | -0.015(-0.006) | -0.020(-0.008) |
| Vertical | 0.371( 0.146) | 0.495( 0.195) |
| **Tail Takeoff** | | |
| Longitudinal | -0.124(-0.049) | -0.165(-0.065) |
| Lateral | -0.282(-0.111) | -0.376(-0.148) |
| Vertical | 0.574( 0.226) | 0.765( 0.301) |
| **Transmission Motions** | | |
| Longitudinal | 0.010( 0.004) | 0.132( 0.052) |
| Lateral | -0.020(-0.008) | -0.028(-0 011) |
| Vertical | 0.264( 0.104) | 0.353( 0.139) |
| Roll | 0.195° | 0.260° |
| Pitch | -0.461° | -0.615° |
| Yaw | -0.247° | -0.329° |
| **Resultant Shaft Coupling Misalignments** | | |
| No 1 Engine | 382° | 0.509° |
| No. 2 Engine | 612° | 0 816° |
| Tail Takeoff | 1.11° | 1.48° |

Allowable misalignment (transient) = 1 0°

Transmission Deflection Effects on Handling Qualities

| | | |
|---|---|---|
| Collective | 3.8% | 5% |
| Cyclic . | 2.3% | 3% |

## 3.5 6 DOF Isolation Risks

Insertion of an isolation system into the main load path of a helicopter most certainly produces a multitude of risk areas. Table III summarizes the the outstanding risk items defined during the design process and Table IV summarizes risks in the areas of system integration. Reduction of the degree of risk for some items such as the basic operation of the isolation system, damping and upper body amplification would be possible through the use of model testing. The model could be a full scale transmission plus isolators mounted on an aiframe mockup which represents the stiffness of the backup structure. Static and dynamic load application systems would be provided. With such a model, the definition of drive shaft misalignments, control system coupling, and operation in a failed configuration (fail safe feature), could be defined. The effect of isolator stiffness and its relationship to the stiffness of the local backup structure could also be investigated. Finally, the procedures for tuning the system could be defined at a tremendous cost savings relative to a flight test environment. This approach to risk reduction and cost savings through ground testing can be extended to a full scale ground test program. Such a plan would involve a much more indepth ground test program to evaluate the isolation system with the potential payoff of elimination of the flight test program. Thoughts and tradeoffs on this concept are presented in the following section.

TABLE III SUMMARY OF RISKS IDENTIFIED IN THE DESIGN PROCESS

| Risk | | Solution | |
|---|---|---|---|
| 1. | Mechanical units function to give isolation in all six degrees-of-freedom | 1. | Early model test to verify |
| 2 | Low damping in mechanical system | 2. | Model test to verify |
| 3 | Higher vibration of transmission mounted components (R&M) | 3. | Component qualification tests to higher g's at NP |
| 4. | Control coupling | 4. | Design compensation linkage - static test to limits |
| 5. | Shaft misalignment | 5. | Design alternate couplings - bench test to limits |
| 6 | Whirl mode stability | 6. | Ground test to verify (or analysis based on ground test defined modes) |
| 7 | Stiffness too high (relative to airframe stiffness) | 7. | Design several stiffnesses which meet load and stress criteria |

TABLE IV. MAIN ROTOR ISOLATION SYSTEM INTEGRATION RISKS

1 Fail safety/failure modes, degraded mode performance

2 Bearing life

3 Inspectability

4 R&M impact - will R&M improvements due to lower fuselage vibration offset degradation in R&M due to increased gearbox vibration and addition of isolation system

5 System life.

6. Tolerances (and tolerance stackups) - and how they affect system performance and production tuning procedures

7. Applicability of system - retrofit, inline change, new helicopter, which fleet aircraft?

8. Cost - compared to other vibration control approaches

## 4.0 Main Rotor Isolation System Demonstration Requirements

In this section, the objectives of the demonstration program for the six degree-of-freedom main rotor isolation system are defined and alternate approaches to satisfy the objectives are reviewed. The alternate approaches considered are 1) a conventional flight test concept feasibility program and 2) a program involving only ground tests. Technical and resource assessments of these competing approaches are made leading to the conclusion that the ground test based approach is more cost effective and technically comprehensive than the flight test demonstration approach.

### 4.1 Objectives of Demonstration Program

The primary objective of the demonstration program is to show that main rotor loads and fuselage vibration can be effectively attenuated in all axes with the proposed 6 degree-of-freedom isolation system design. The demonstration program can also be viewed as showing the feasibility of expanding main rotor isolation to 6 degrees-of-freedom from prior systems of lesser capability which have been demonstrated satisfactorily (References 2, 5 and 6). The specific characteristics which will be assessed during the demonstration program to evaluate feasibility are:

1) Isolation system performance; attenuation of transmitted loads and fuselage vibration attenuation.

2) Isolation system loads and stresses.

3) Deflections at critical interfaces.

4) Aeromechanical stability and handling qualities.

5) Failure modes.

These characteristics are to be examined for level flight and maneuver loading conditions to cover a realistic functional flight envelope and to show what happens with system bottoming beyond that.

### 4.2 Alternate Demonstration Approaches

Two demonstration approaches are examined to determine the technical and resource advantages of each. They are:

1) A conventional flight test concept feasibility program.

2) A ground test based program built around an "Iron Bird" static and dynamic test.

Summaries of all the tasks necessary to perform the demonstration programs for the two approaches are shown in Table V. For the flight test approach, the functional suitability of the isolation system is verified by a sequence of tests:

- System model tests
- Laboratory functional tests of isolator units
- Airframe shake tests
- Aircraft ground static tests (breakout forces)
- Aircraft ground dynamic tests
- Aircraft flight tests

In addition to these functional tests several additional tests are required to insure safety of flight:

- Laboratory fatigue and proof load tests of isolator unit
- Laboratory fatigue test of high speed shaft couplings
- Aircraft ground static tests to verify absence of controls coupling and acceptable deflections at critical interfaces

The ground test based approach uses the following tests to substantiate the functional suitability of the isolation system:

- System model tests
- Laboratory functional tests of isolator units
- "Iron Bird" static and dynamic tests
- Airframe shake tests

Since this approach precludes the need for flight test there are no tests required to protect flight safety. Handling Qualities and Aeromechanical Stability are verified by analysis using fuselage dynamic modes from the ground shake tests.

The "Iron Bird" test is a comprehensive experiment during which static and dynamic flight loads are simultaneously applied to a system which exactly represents the isolation system and simulates the aircraft structure. The functional specification for the "Iron Bird" test facility constitutes Table VI.

## Table V

### 6 Degree-of-Freedom Main Rotor Isolation Demonstration Approaches

**Flight Test Demo**

- Select aircraft for test
- Aeromechanical design analyses
- Model tests (if required)
- Design and fab isolation system
- Design and fab isolation system/fuselage interface hardware
- Lab functional tests of isolator units
- Lab proof load and fatigue tests
  - Isolators
  - Shaft couplings
- Modify aircraft to install isolation system
  - Transmission support beams
  - Transmission housing
- Modify aircraft peripheral system
  - Controls (motion compensation linkage)
  - High speed shaft couplings

**Ground Test Demo**

- Select aircraft fuselage for test
- Aeromechanical design analyses
- Design and fab isolation system
- Design and fab isolation system/fuselage interface hardware
- Lab functional tests of isolator units
- Build up Iron Bird test facility
- Conduct Iron Bird Tests (static and static + dynamic flight loads, multi-axis level flight, maneuvers, limit loads)
  - Deflections at critical interfaces
  - Control compensation linkage requirements defined
  - Friction and breakout forces (static and dynamic)
  - Isolation system functional/tuning characteristics
  - Stress/load sensitivities

Table V - (cont'd)

Flight Test Demo

- Build up aircraft with isolation and peripheral systems
- Aircraft ground static tests
  - Controls coupling
  - Friction and breakout forces
  - Deflections at critical inter faces
- Aircraft ground shake test
  - Isolation system functional/ tuning characteristics
  - Breakout vibratory force levels (1g static load)
  - Stress/load sensitivities
  - Ground and air resonance shake tests
- Bring aircraft to flight status and instrumentation
- Aircraft ground/flight tests
  - Ground and air resonance evaluation
  - Isolation system tuning surveys
  - Level flight vibration and loads/ stress/deflection surveys
  - Maneuver vibration and loads/stress/ deflection survey
  - Handling qualities evalaution
- Return aircraft to original configuration
- Ground test & flight test data reduction and analyses
- Documentation

Ground Test Demo

- Aircraft ground test
  - Define effects of real fuselage structure on isolation system performance and tuning
  - Ground and air resonance shake tests
- Ground test data reduction and analysis
- Documentation

Table VI

Iron Bird Rotor Isolation System Test Facility Specification

- Duplication of aircraft isolation system
- Isolation system geometry and tolerances of aircraft quality
- Simulation of aircraft gearbox mass and inertias
- Simulation of aircraft transmission support structure, geometry and flexibility
- Simulation of airframe dynamic coupling with spring supported rigid body mass
- Capability of applying full limit flight loads in static and dynamic testing
- Multi-axis load application
- Vibratory, transient and static load application systems dynamically uncoupled from transmission motions
- Full measurement package for loads, stresses, deflections and vibration
- Complete data acquisition system, compatible with Sikorsky computerized processing system.

## 4.3 Technical Assessment of Flight Test and Ground Test Approaches

Table VII summarizes the technical advantages of the ground test based and flight test based demonstration approaches. The table only considers those activities which are used to evaluate the functional suitability of the system. Tests to support flight safety are not included. Component laboratory tests and airframe shake tests are common to both approaches so there is no relative advantage to consider. The assessment of the two approaches reduces to determining relative technical advantages of an "Iron Bird" ground test versus aircraft static ground tests and flight tests. The major advantages of the "Iron Bird" ground tests are:

- Load/stress/deflection/vibration surveys more controlled and comprehensive than flight test because applied loads are known and sensitivities to load perturbations can be determined.
- Limit loads can be applied.
- Effect of isolator unit failure can be determined.
- Isolation system nonlinearities can be studied.
- A wider range of load and tuning sensitivity tests can be conducted.
- Evaluation of isolation system concept is more generic.
- Technical effort will not be diluted by need to solve retrofit design and test problems.
- Not containinated by NP vibratory inputs (during flight) from other known (or unknown) sources which could affect apparent isolation performance.

The major disadvantage of the ground test based approach compared to flight test is that the evaluation of aeromechanical stability and handling qualities will have to be based on analyses using aircraft dynamic characteristics from ground shake tests. This approach is technically sound, however, and supportable by good correlation on past programs.

TABLE VII

Comparison of Technical Advantages of Ground Test Demo and Flight Demo of 6 DOF Main Rotor Isolation System

| | | Grnd Test Demo | | | Flight Test Demo | |
|---|---|---|---|---|---|---|
| Demonstration Task | Analysis+ | Iron Bird Test | Component Lab Tests | A/F Shake Test | A/C Grnd Shake Test | A/C Flt Test |
| 1. Isolator unit damping | | | * | | | |
| 2. Isolator unit tuning | | | * | | | |
| 3. Isolator unit performance | | | * | | | |
| 4. Isolation system damping | | | | | | |
| Unloaded | * | | | * | | * |
| . 1g loads | * | | | * 1g lift | | * |
| . Maneuvers | * | | | | | |
| . Limit loads | * | | | | | |
| 5. Isolation system tuning | | | | | | |
| . Unloaded | * | | | * | | Limited by no. of flts. |
| . 1g loads | * | | | * 1g lift | | |
| . Maneuvers | * | | | | | |
| . Limit loads | * | | | | | |
| . Sensitivity to vibratory load level | * | | | * | | |
| . Effect of A/F dynamics | Parametric | | | * | | by deduction only |
| 6. Isolation system performance (vibration attenuation) | | | | | | |
| . Level flight | * | | | * | | * |
| . Maneuvers | * | | | | | * |
| . Limit loads | * | | | | | |
| . When 1 or more units bottom | * | | | simulated | | depend on V-N envelope |

TABLE VII (cont'd)

Comparison of Technical Advantages of Ground Test Demo and Flight Demo of 6 DOF Main Rotor Isolation System

| | Demonstration Task | Analysis+ | Grnd Test Demo: Iron Bird Test | Grnd Test Demo: Component Lab Tests | Grnd Test Demo: A/F Shake Test | Flight Test Demo: A/C Grnd Shake Test | Flight Test Demo: A/C Flt Test |
|---|---|---|---|---|---|---|---|
| 7. | Deflections at critical interfaces | | | | | | |
| | . Level flight | | * | | limited to 1g lift | limited | * |
| | . Maneuvers | | | | | (for lift = 0) | * * |
| | . Limit loads . | | * | | | | |
| | . As a function of parametric application of vibratory loads | | * | | * | | |
| | . When one unit fails | | * | | * | | |
| 8. | Isolation system loads & stresses | | | | | | |
| | . Level flight | | * | | limited | | * |
| | . Maneuvers | | * | | | | * |
| | . Limit loads | | * | | | | |
| | . As a fct. of parametric load application | | * | | | | |
| | . When one unit fails | | * | | * | | |
| 9. | Isolation system breakout forces | | | | | | |
| | . Level flight loads | | * | | limited to 1g lift | limited by deduction (for lift only = 0) | |
| 10. | Aeromechanical stability evaluation | use modes from shake test | | | defines modes for A/M stab anal. | | * |
| 11. | Handling qualities evaluation | GENHEL (use modes from shake test | | | define modes for H.Q. anal. | | * |

+ Analyses listed are those required in lieu of flight test only. Analyses to support design tasks are also performed.

## 4.4 Resource Assessment of Flight Test and Ground Test Approaches

A comparison of tasks required to perform the alternate demonstration programs is presented in Table VIII. Major cost advantages are seen for the ground test based program because of the elimination of significant design and test tasks. Specifically, the following flight test based program requirements are eliminated by adopting the ground test approach:

- Need for an aircraft in flight status.
- Aircraft flight loads and vibration instrumentation package.
- Need for flightworthy hardware.
- Modifications to the basic fuselage and transmission to install the isolation system.
- Control compensation linkage and high speed shaft coupling modifications.
- Lab proof load and fatigue tests of isolators and shaft couplings.
- Aircraft ground static tests.
- Aircraft flight tests.
- Requirement to return aircraft to original configuration.

The "Iron Bird" tests represent an additional item, however, relative to the flight test program.

## Table VIII

### Task Comparison - Ground Test Demo vs Flight Test Demo

| | Task | Flt Test | Grnd Test |
|---|---|---|---|
| 1. | Aeromechanical Analyses | * | * |
| 2. | Model Tests | * | * |
| 3. | Design and Fab | | |
| | . Isolation system | * | * |
| | . Interface plate | * | * |
| | . Transmission support beam mods | * | |
| | . Control compensation linkage | * | |
| | . High speed shaft couplings | * | |
| 4. | Lab Tests | | |
| | . Isolator unit function | * | * |
| | . Isolator unit fatigue/proof loads | * | |
| | . Shaft coupling fatigue | * | |
| 5. | Ground Tests | | |
| | . Iron Bird test | | * |
| | . A/C static tests (friction, deflections) | * | |
| | . A/C shake test | * | * |
| 6. | Flight Tests | | |
| | . A/C prep to flt status | * | |
| | . Instrumentation | * | |
| | . 20 hr flight program | * | |
| | . Return A/C to original condition | * | |
| 7. | Data Analysis and Documentation | * | * |

## 4.5 Conclusion

The technical and resource requirements assessments of the ground and flight test based main rotor isolation demonstration approaches has led to the conclusion that the ground test based approach is the more technically comprehensive and cost-effective of the two. The ground test based approach is formulated around an "Iron Bird" test in which flight isolation system hardware is exactly represented and aircraft hardware is simulated. Flight loads including steady and vibratory components are applied to the system up to limit load levels. Load/stress/vibration/deflection surveys conducted with known applied loads permits parametric evaluations as well as assessment of system performance at specific flight conditions. The effect that the fuselage dynamic characteristics have on isolation system performance are studied parametrically on the "Iron Bird" and confirmed for a specific fuselage during a full airframe shake test.

Overall, the ground test based approach is considered to be a more generic demonstration of the concept. Therefore the results of the program would be applicable to all future installations. Peripheral systems necessary to install the isolation system on a particular helicopter, such as high speed shaft couplings and control motion compensation linkages are addressed by providing design deflection requirements.

The ground test approach also eliminates the need for costly, non generic, one-of-a-kind modifications necessary to retrofit an existing helicopter with the 6 DOF isolation system.

## 5.0 Conclusions and Recommendations

A preliminary design study of six degree-of-freedom helicopter main rotor isolation has been completed leading to the following conclusions:

1) The capability to isolate in all six degrees-of-freedom is desirable because significant hub vibratory loads can occur in all axes depending upon helicopter configurations and flight conditions.

2) An isolation system arrangement has been devised which provides for greater than 90% isolation in all axes and which has a weight penalty of approximately 1% of gross weight.

3) The isolation system embodies the antiresonance concept; four two-dimensional isolator units are arranged to provide system isolation for the six degrees-of-freedom.

4) The key design issues for the isolation system are identified as damping and deflections. Damping levels of the order of 1% critical are required. A stiffness of 131,400 N/cm (75,000 lb/in) unit is required to satisfy static deflection and strength requirements.

5) Two approaches for demonstration of the isolation system concept have been evaluated; a flight test demonstration and a ground test approach formulated around an "Iron Bird" experiment. The ground test approach is shown to be more comprehensive, generic and cost effective for the goal of concept verification.

6) It is recommended that six degree-of-freedom main rotor isolation be carried forward into the concept demonstration phase.

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16 Abstract


ABSTRACT

A preliminary design study has been performed wherein the design requirements of a six degree-of-freedom rotor isolation system have been defined and an isolator concept which satifies these requirements identified. Primary design objectives for the isolation system are 90% attenuation of all NP main rotor shaft loads at a weight penalty $\leq$ 1% of design gross weight. The configuration is sized for a UH-60A BLACK HAWK helicopter and its performance, risk, and system integration are evaluated through a series of parametric studies. Preliminary design was carried forward to insure that the design is practical and that the details of the integration of the isolator into the helicopter system are considered. Alternate ground and flight test demonstration programs necessary to verify the proposed isolator design are defined. Technical and cost assessments of these competing approaches indicate the ground test based approach is technically more generic and more cost effective than the flight test demonstration.


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